DOCUMENT RESUME

ED 153 793 SE 023 947

TITLE Identification and Control of Pollution from Salt Water Intrusion.
INSTITUTION Environmental Protection Agency, Washington, D.C. Office of Water Programs.
REPORT NO EPA-430/9-73-013
PUB DATE 73
NOTE 104p.
AVAILABLE FROM Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 ($1.25)

EDRS PRICE MF-$0.83 HC-$6.01 Plus Postage.
DESCRIPTORS Environment; *Federal Legislation; Geology; *Management; Natural Resources; Oceanology; *Pollution; Reference Materials; *Water Pollution Control; *Water Resources
IDENTIFIERS *Salt Water Intrusion; *Waste Water Treatment

ABSTRACT

This document contains informational guidelines for identifying and evaluating the nature and extent of pollution from salt water intrusion. The intent of these guidelines is to provide a basic framework for assessing salt water intrusion problems and their relationship to the total hydrologic system, and to provide assistance in developing areawide waste treatment management plans in accordance with the requirements of the Federal Water Pollution Control Act. (CS)

IDENTIFICATION AND CONTROL OF POLLUTION FROM SALT WATER INTRUSION

UNITED STATES
ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460
1973

FOREWORD

Degradation of the quality of fresh surface and ground waters by intrusion of saline water is a common and complex problem in both coastal and inland areas. Seldom is the problem the direct result of waste disposal. More often it is the inadvertent result of man's activities as he alters his environment.

The Federal Water Pollution Control Act Amendments of 1972 require the Administrator of the Environmental Protection Agency to issue information on identification and control of pollution from salt water intrusion (subsection 304(e)(1&2)(E)). This report is issued pursuant to that legislative mandate.

Russell E. Train
Administrator

EPA-430/9-73-013

IDENTIFICATION AND CONTROL OF POLLUTION FROM SALT WATER INTRUSION

United States Environmental Protection Agency
Office of Air and Water Programs
Water Quality and Non-Point Source Control Division
Washington, D. C. 20460
1973

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price $1.25

CONTENTS

PART I

GUIDANCE FOR IDENTIFICATION

AND EVALUATION OF THE

NATURE AND EXTENT OF POLLUTION FROM SALT WATER INTRUSION

PART II

PROCESSES, PROCEDURES AND METHODS FOR CONTROL OF POLLUTION FROM SALT WATER INTRUSION

List of Figures

GUIDANCE FOR IDENTIFICATION AND EVALUATION OF THE NATURE AND EXTENT OF POLLUTION FROM SALT WATER INTRUSION

INTRODUCTION

Section 304(e) of the Federal Water Pollution Control Act as Amended 86 Statute 816; 33 U.S.C. 1314 (1972) provides that:

"The Administrator (of EPA)....shall issue....within one year after the effective date of this subsection (and from time to time thereafter) information including (1) guidelines for identifying and evaluating the nature and extent of non-point sources of pollutants, and (2) processes, procedures, and methods to control pollu ion resulting from -...

(E) salt water intrusion resulting from reductions c fresh water flow from any cause, including extractic of ground water, irrigation, obstruction, and diversion;...

This document has been prepared by the United States Environmental Protection Agency in response to the requirements of Section 304(e)(1)(E) of the Act.

The following sections contain informational guidelines for identifying and evaluating the nature and extent of pollution from salt water intrusion. The circumstances surrounding local salt water intrusion problems vary widely and a uniform "cook book" approach to problem identification and evaluation is not possible. Accordingly, this guidance is not intended to provide a step-by-step procedure for field reconnaissance or sampling techniques. Knowledge of the existence and delineation of the spatial distribution of waters contaminated by salt water intrusion will serve little useful purpose by itself. If salt water intrusion is to be effectively controlled it must be understood and evaluated in the context of the causal factors within the drainage basin. The intent of these informational guidelines is to provide a basic framework for assessment of salt water intrusion problems and their relationship to the total hydrologic system, and to aid State authorities in developing areawide waste treatment management plans in accordance with the provisions of Section 208 of the Federal Water Pollution Control Act as Amended.

CAUSES OF SALT WATER INTRUSION

Salt water intrusion ... ..into surface or ground water is a complex situation controlled by the geologic and hydrologic characteristics of the area. Natural water systems are dynamic. They respond in quality and quantity to natural phenomena and to man's activities such as changes in land use, stream channel linings, and consumptive withdrawal. Identification and evaluation of the nature and extent of salt water intrusion begins with an understanding of the general mechanisms by which intrusion occurs.

Sea Water Intrusion in Coastal Aquifers

Under natural conditions fresh ground water in coastal aquifers is discharged into the ocean at or seaward of the coastline. A balance or equilibrium tends to become established between the fresh ground water and the salt water pressing in from the sea. Where coastal aquifers are overpumped, lowered by natural drainage, or natural recharge is impeded by construction or other activities, the ground water level, whether water table in unconfined aquifers or piezometric surface in confined aquifers, is lowered thereby reducing the fresh water flow to the ocean. The interface between the fresh and saline water has a parabolic form with the saline water tending to underride the less dense fresh water. The reversal or reduction of fresh water flow allows the heavier saline water to move into areas where only fresh water previously existed. Thus, even with a seaward pressure gradient, sea water can advance inland. Because of the high salt content of sea water, as little as two percent of it mixed with fresh ground water can make that portion of the aquifer unusable in relation to the U.S. Public Health Service drinking water standard for total dissolved solids. Only a small amount of intrusion can have serious implications regarding the future use of an aquifer as a water supply source.

Upstream Encroachment of Sea Water

The interaction of river flow and tidal currents results in a net upstream movement of sea water along the bottom with fresh water overriding this wedge in a seaward direction. The position of the interface between the fresh water and the sea water is dependent on channel geometry, river discharge, and high tide height. A change in any of these parameters will cause the salt water/fresh water interface to migrate. The most common causes of upstream encroachment of sea water are deepening of navigation channels, construction of sea level canals, and reduction of stream flow. Reduction of stream flow or deepening of channels results in landward migration of the sea water wedge while increased stream flow results in a seaward migration. Sea water encroachment can contaminate both surface and subsurface water supplies, render fish and wildlife habitats unsuitable for native populations, and through increased corrosion shorten the life expectancy of engineering structures.

Intrusion in Inland Aquifers

Large quantities of saline water exist under diverse geologic and hydrologic environments in the United States. Most of the Nation's largest sources of fresh ground water are in close proximity to natural bodies of saline ground water. Interaquifer transfer of saline waters results f om two basic mechanisms. One involves the upward migration of saline waters into fresh water aquifers as a result of man-induced changes in the hydrologic pressure regime. The other involves the direct transfer of saline waters vertically through wells or other penetrations. Because of the relatively slow movement of ground water, any saline water intrusion may produce detrimental effects on ground water quality that could persist for months or years after the intrusion has ceased.

EXTENT OF POLLUTION FROM SALT WATER INTRUSION

Salt water intrusion problems are ubiquitous in coastal areas and surprisingly widespread in inland areas. On the highly populated Atlantic Coast, between Massachusetts and Florida, each of the States has reported problems with sea water intrusion. The seriousness of the problem is usually dependent on the intensity of urban and industrial development with its attendant withdrawal and non-return of water.

On the West Coast, California has had many problems with sea water intrusion and has spent considerable effort trying to solve or ameliorate the problem. Approximately two thirds of the conterminous United States are underlain by saline waters containing more than 1,000 mg/l dissolved solids, and the problem of salt water intrusion in inland aquifers can be the same as in coastal areas. Only eight of the fifty States do not report significant salt water intrusion problems.

IDENTIFICATION OF POLLUTION FROM SALT WATER INTRUSION

Most intrusion of salt water into fresh water can be ascribed to one of three primary mechanisms: the reversal or reduction of fresh water discharge which allows the heavier saline water to move into an area where only fresh water previously existed; the accidental or inadvertant destruction of natural barriers that formerly separated bodies of fresh and saline waters; or the accidental or inadvertant results of the disposal of waste saline water.

Major elements in an assessment of the occurrence and extent of salt water intrusion should include:

1. spatial delineation of primary aquifers and streams,
2. analysis of historical water quality (salinity) data for suspect areas, to establish trends,

3. establishment of a salinity monitoring network for surface and ground water,
4. monitoring the location of the fresh water/salt water interface,
5. basin wide hydrogeologic investigations where saline intrusion occurs to identify causal factors.

Prime areas for consideration should include rapidly developing coastal areas where demands for fresh water result in a reduction or reversal of flow gradient; and areas of coastal waterway or embayment construction, or deepening of navigation channels where natural barriers to salt water flow may be breached. Another prime example of breaching of confining strata is encountered in drilling operations, especially in oil producing areas where salt water may move great distances along broken or corroded well casings or improperly abandonded wells. Not to be overlooked as a source of pollution is any operation that disposes of waste saline waters, whether disposal is directly to surface streams or to the ground water through evaporation pits or other methods.

In other than oil producing areas salt water intrusion is seldom the direct result of waste disposal. More often it is the natural adjustment of the hydrologic system to the many stresses placed upon it. Fundamental to an evaluation of the extent of salt water intrusion is the need for comprehensive hydrogeological investigations of the surface and subsurface water systems. Identification and evaluation of the extent of salt water intrusion should be an integral part of each State's water quality monitoring program required under section 106(e)(1) of the Act, with salinity one of the parameters routinely monitored throughout the water quality network.

As an initial step in the evaluation of the nature and extent of salt water intrusion principal aquifers must be spatially defined, and historical water quality records for both surface and ground waters should be collected and contour maps of salt concentration compiled. In this way, natural or base line conditions can be established and the location of the salt water/fresh water interface can be displayed in relation to the water requirements of the hydrologic basin. Updating of such maps from current monitoring data provides a rapid indication of the advance or retreat of the salt water wedge. Under normal conditions monitoring points should be measured for salinity (or total dissolved solids) or checked for electrical conductivity at one to two month intervals. More frequent measurements may be warranted if encroachment is in the proximity of major water supply sources.

Most salt water intrusion problems will be encountered in heavily populated coastal areas. In many cases extensive water quality monitoring programs will have been in effect and will provide most or all of the water quality data required for determining the present extent of salt water intrusion in that area. Salinity measurements of both surface and ground waters should be an integral part of the State's water quality monitoring program and form the basic data input for continuous evaluation of the extent of salt water intrusion.

An inventory of existing monitoring points for both surface and ground waters which may be used in determining the salinity of streams and principal aquifers should be undertaken by each State, and additional monitoring stations installed as part of the State's water quality monitoring network where necessary for adequate spatial coverage. In situ measurement of electrical conductivity can provide an indication of salt content in surface and ground waters without collecting water samples for laboratory analysis.

Sampling information for each surface or subsurface monitoring station should include:

1. location by latitude, longitude and elevation,
2. stream or aquifer identification and date,
3. depth or depths of samples,
4. stream velocity,
5. temperature,
6. electrical conductivity, TDS, or chloride concentration,
7. depth to water table.

Where a rise in electrical conductivity is noted, samples should be analyzed for increased salinity. Automatic recording devices can be installed for continuous electrical conductivity monitoring, and should be incorporated in the State's water quality monitoring network. Any water samples that are taken for laboratory analysis should be secured and preserved according to standard methods as described in Methods for Examination of Water and Wastes, (U.S. Environmental Protection Agency, 1971).

Where salt water intrusion in either surface or ground water is suspected or know to exist, a comprehensive hydrogeological investigation should be designed to provide requisite information for planning and control programs. The type of information that may be required could include:

1. the geologic structure of the surface and ground water basins and their boundaries;

2. the nature and hydraulic characteristics of the subsurface formations including:

   a. rock type
   b. degree and type of porosity
   c. permeability
   d. reservoir pressure
   e. degree of hydraulic continuity with surface waters.

3. surface water and ground water levels, and directions and rates of movement and seasonal fluctuations;

4. surface water and ground water quality, particularly natural chlorides content;

5. sources, locations, amounts, and quality of natural recharge;

6. locations, amounts, and quality of artificial recharge;

7. locations and amounts of extractions.

Historical information of this type is generally available, to some degree, in published form from Federal, State, and local agencies that are concerned with water resources. Additional information of this type can be derived from a variety of investigative techniques including but not limited to:

1. geologic reconnaissance,

2. geophysical surveys,
3. examination of well logs,
4. test holes,
5. well pumping tests,
6. measurement of surface and ground water levels,
7. chemical analysis of samples of surface and ground waters,
8. analysis of precipitation and runoff records.

Techniques for predicting the location and extent of salt water intrusion mainly rely on mathematical analysis of aquifer and stream parameters, and tidal characteristics. The level of sophistication and predictive ability of analytical techniques varies from simple extrapolation of the time of arrival of the salt water/fresh water interface at successive observation wells to highly complex numerical models of the entire hydrologic system. Discussion of the application of these techniques is beyond the scope of this report but selected references to detailed explanations are included at the end of this section.

The areal extent and depth of detail of the investigations will vary with the extent of the water basin or aquifer that has been or may be affected, and the present and prospective uses of the water resources. The investigations should be designed to define the water budget of the basin or aquifer in sufficient detail to allow prediction of the volumes and rates of surface and ground water flow necessary to arrest and reverse the salt water advance. Such information will be an integral part of the data base used in basin wide water use planning, management, and pollution control programs.

EVALUATION OF THE EFFECTS OF SALT WATER INTRUSION

As surface and ground waters are integral parts of the same hydrologic whole, changes in the salinity concentration of one will most likely affect the salinity concentration of the other. If the objective of a salt water intrusion control program is to maintain zero increase in the salinity of fresh water resources, this objective is seldom attainable especially in areas of high water use. Nor is it possible to define a single optimal or tolerable salinity concentration for "fresh waters". These concentrations are dependent on the use that is to be made of the water. Water devoid of dissolved materials is intolerable in nature because pure water will not support life. Natural waters contain endless varieties of dissolved materials in concentrations that differ widely from one locality to another as well as from time to time. The chlorides, sulfates, carbonates, and bicarbonates of sodium, potassium, calcium, and magnesium are generally the most common salts present. Different organisms vary in their optimum salinity requirements as well as in their ability to live and thrive under variations from the optimum.

Any evaluation of the potential effects of salt water intrusion must be performed in the context of its effect on the total dissolved solids of the receiving water and the water use requirements.

Optimal and tolerable salinity concentrations will be different for such uses as: public water supplies, fish and wildlife production, and agricultural uses. Waters with less than about 500 mg/l total dissolved solids are generally considered suitable for domestic purposes, while waters with greater than about 5,000 mg/l TDS generally are unsuitable for irrigation purposes. Maximum salinity concentrations for livestock consumption vary from less than 3,000 mg/l TDS for poultry to as much as 12,000 mg/l TDS for sheep. A more detailed analysis of salinity requirements for various water uses is contained in <u>Water Quality Criteria</u>, (U.S. Environmental Protection Agency, 1972).

Evaluation of the nature, extent and effects of salt water intrusion may vary from simple plots of water quality that indicate the position of the salt water/fresh water interface to sophisticated mathematical models of the entire surface and ground water basin. Such models can be used to predict the response of the salinity concentration to various types of stresses at any point in the system and allow for long-range basin planning and comprehensive intrusion control programs. The degree of sophistication of analysis required will vary in proportion to the complexity of the hydrologic system and the water demands for the area. Regardless of the level of analysis involved the objective of the water quality monitoring and hydrogeologic investigations should always be to relate salt water intrusion to its causal factors. Only in this way can water use planning be accomplished in a manner that will maintain the hydrologic balances necessary to control salt water intrusion.

Sources of Additional Information

1. Fayers, F.J., and Sheldon, J.W., 1962, "The Use of a High Speed Digital Computer in the Study of the Hydrodynamics of Geologic Basins": Jour. Geophys. Res., V. 67, no. 6, p. 2421-2431.

2. Freeze, R.A., 1971, "Three-dimensional, Transient, Saturated-Unsaturated Flow in a Ground Water Basin": Water Resour. Res., v. 7, no. 2, p 347-366.

3. Freeze, R.A., and Witherspoon, P.A., 1966-8, "Theoretical Analysis of Regional Ground Water Flow": Part 1, Water Resour. Res. v. 2, no. 4, p. 641-656, 1966 Part 2, Water Resour. Res. v. 3, no. 2, p. 623-634, 1967 Part 3, Water Resour. Res. v. 4, no. 3, p. 581-590, 1968

4. Ippen, Arthur T., "Salt-Water Fresh-Water Relationships in Tidal Channels", Proceedings of the Second Annual American Water Resources Conference, 1966.

5. Kashef, Abdel-Azis, F., "Model Studies of Salt Water Intrusion", Water Resources Bulletin, Vol. 6, No. 6, P944-967, 1970.

6. Pinder, George F., "A Numerical Technique for Calculating the Transient Position of the Salt Water Front", Water Resources Research, Vol. 6, No. 3, P 875-882, 1970.

7. Pinder, G.F., and Frind, E.O., "Application of Galerkin's Procedure to Aquifer Analysis": Water Resour. Res., V.8, no. 1, p. 108-120. 1972.

8. U.S. Environmental Protection Agency, Subsurface Water Pollution - A Selective Annotated Bibliography - Part II - Saline Water Intrusion, 1972.

9. Witherspoon, P.A., Javandel, I., and Neuman, S.P., Use of the Finite Element Method in Solving Transient Flow Problems in Aquifer Systems: p. 687-698 in The Use of Analog and Digital Computers in Hydrology (vol. 2): Internat. Assoc. Sci. Hydrol. Publ. No. 81. 1968.

PROCESSES, PROCEDURES AND METHODS FOR CONTROL OF POLLUTION FROM SALT WATER INTRUSION

INTRODUCTION

This information has been prepared by the United States Environmental Protection Agency in response to the requirements of Section 304(e)(2)(E) of the Federal Water Pollution Control Act as Amended 86 Statute 816; 33 U.S.C. 1314 (1972). Discussed herein are processes, procedures, and methods for control of pollution from salt water intrusion. The purpose of this information is to provide a basic framework for assessment of salt water intrusion problems and their relation to the total hydrologic system, and to aid State authorities in developing salt water intrusion surveillance and control programs in accordance with the provisions of the Act. The treatment of the topic is not intended to be comprehensive or exhaustive, since this would take many volumes. Rather, the intent is to be as concise as possible, addressing those aspects felt to be most important, with liberal use of selected references for more detailed explanations. Revision, expansion, and more detailed treatment of selected aspects of salt water intrusion control will be accomplished under the provisions of the Act that require periodic updating of such information.

WATER QUALITY AND POLLUTION

The quality of water refers to its chemical, physical, and biological characteristics. All naturally occurring waters contain dissolved mineral constituents, all possess characteristics such as temperature, taste, and odor, and some contain organisms such as bacteria. The natural quality of water depends upon its environment, movement, and source. For the purposes of this report, pollution is defined as the man-induced degradation of the natural quality of water. The particular use to which water can be placed depends, of course, upon its quality. However, the various criteria defining the suitability of a water for municipal, industrial or agricultural use are not considered in describing pollution. Instead, the measure of pollution is a detrimental change in the given natural quality of water. This may take the form, for example, of an increase in chloride content, of a rise in temperature, or of the addition of E. coli bacteria.

Hydrogeological Investigations

A fundamental concept applicable to almost all water pollution control situations and inherent in all of the processes, procedures, and methods for control of salt water intrusion discussed in this report is the need for comprehensive hydrogeological investigations before initiating control procedures. The geologic and hydrologic environment of each water resource system is unique. Ground water systems are far more complex and slower reacting than surface water systems.

Water resource systems are dynamic in nature. Surface and ground water resources are integral parts of the same hydrogeological whole. They respond both in quantity and quality to natural phenomena and to man's activities including changes in land use, stream channel lining, and artificial recharge. Quality changes result from a variety of causes of which waste discharge is only one.

Developed ground water systems are subject to both seasonal changes and long term trends. In the case of salt water intrusion, pollution may not be the result of waste discharge but rather the natural response of the hydrologic system to the various stresses placed upon it. Because of the dynamic nature of water resource systems, the historic behavior of the systems involved must be studied as well as future responses to anticipated changes in man's influences. The longer the period and the more extensive the available records, the better will be the evaluation of the system. For stressed systems, continuing data collection and periodic reevaluations are essential for the eventual elimination of pollution. Regardless of the level of sophistication of analysis required the objective of the hydrologic investigations should always be to relate salt water intrusion to its causal factors.

SEA WATER INTRUSION IN COASTAL AQUIFERS

Scope of the Problem

Under natural conditions fresh ground water in coastal aquifers is discharged into the ocean at or seaward of the coastline. If, however, demands by man for ground water become sufficiently large, the seaward flow of ground water is decreased or even reversed. This allows the sea water to advance inland within the aquifer, thereby producing sea water intrusion.

This section briefly describes the history of sea water intrusion; occurrence of such intrusion in the United States, and the environmental consequences, causal factors, and movement of sea water in the underground. Thereafter, control methods and monitoring procedures are presented, together with references to sources of additional information.

Emphasis in this section is on control of the lateral movement of sea water underground. Control of vertical flow mechanisms causing intrusion are presented subsequently.

History

Sea water intrusion developed as costal population centers over-developed local ground water resources to meet their water supply needs. The earliest published reports, dating from mid-19th century in England, describe increasing salinity of well waters in London and Liverpool. As the number of localities experiencing intrusion has grown steadily with time, so has recognition of the problem. Today, sea water intrusion exists on all continents as well as on many oceanic islands.

More than 70 years ago two European investigators found that saline water occurred underground near the coast at a depth of about 40 times the height of fresh water above sea level. This distribution, known as the Ghyben-Herzberg relation after its discovers, is related to the hydrostatic equilibrium existing between the two fluids of different densities. Although coastal intrusion is a hydrodynamic rather than a hydrostatic situation, the relation is a good first approximation to the sea water depth for nearly horizontal flow conditions. Where head differences in the two fluids exist, refinements in the relation (Luscynski and Swarzenski, 1966) give improved results.

Intrusion in the United States

Almost all of the coastal states of the United States have some coastal aquifers polluted by the intrusion of sea water. Florida is the most seriously affected state, followed by California, Texas, New York, and Hawaii.

The Florida problem stems from a combination of permeable limestone aquifers, a lengthy coastline, and the desire of people to live near the pleasant coastal beaches. Intrusion has been identified in 28 specific locations (Black, 1953). Some 18 municipal water supplies have been adversely affected since 1924. In the Miami area intrusion has long been a problem and was seriously augmented by interior drainage canals which lowered the water table and permitted sea water to advance inland by tidal action.

In California, the large urban areas concentrated in the coastal zone have caused sea water intrusion in 12 localities; seven others are threatened, and 15 others are regarded as potential sites (California Department of Water Resources, 1958). Most of the affected areas contain confined aquifers, and salinity increases can be traced to the lateral movement of sea water induced by overpumping. Major programs to control intrusion have been implemented in Southern California. In Texas, intrusion is occurring in the Galveston, Texas City, Houston, and Beaumont-Port Arthur areas and around Corpus Christi. Saline water is moving up-dip from the Gulf of Mexico in the confined Coastal Plain sediments. The problem in New York is centered around the periphery of the heavily pumped western half of Long Island. The basalt aquifers of Honolulu, Hawaii have been extensively intruded by sea water due to continued overdraft conditions.

Environmental Consequences

Because of its high salt content, as little as two percent of sea water mixed with fresh ground water can make that portion of the aquifer unusable in terms of the U.S. Public Health Service drinking water standard for total dissolved solids. Thus, only a small amount of intrusion can seriously threaten the continued use of an aquifer as a water supply source.

Once invaded by sea water, an aquifer may remain polluted for decades. Even with application of various control mechanisms, the normal movement of ground water precludes any rapid displacement of the sea water by fresh water. Prolonged abandonment or restricted use of the underground resource may be required.

Causal Factors

The usual cause of sea water intrusion in coastal aquifers is over-pumping. Pumping lowers the ground water level. The effect is depression of the ground water table in unconfined aquifers or alterations of the piezometric surface in confined aquifers. Either event will reduce the fresh water flow to the ocean. Thus, even with a seaward gradient, sea water can advance inland. If pumping is sufficiently great to reverse the gradient oceanward, fresh water movement ceases and sea water may invade the entire aquifer.

In flat coastal areas, drainage channels or canals can cause intrusion, in two ways. One is the reduction in water table elevation and its associated decrease in underground fresh water flow. The other is tidal action. If the channels are open to the ocean, tidal action can carry sea water long distances inland through the channels, where it may infiltrate and form fingers of saline water adjoining the channels.

In most oceanic islands fresh water forms a lens overlying sea water. If a well within the fresh water body is pumped at too high a rate, the underlying sea water will rise and pollute the well. Wells can also serve as means of vertical access; sea water in one aquifer may move into a fresh water aquifer lying above or below the saline zone.

Pollutant Movement

The interface between underground fresh and saline waters has a parabolic form. The salt water tends to underride the less-dense fresh water. Under equilibrium conditions, the sea water/fresh water interface is essentially stationary, while the fresh water flows seaward.

The length of the intruded wedge of sea water varies inversely with the magnitude of the fresh water head. Thus, a reduction of fresh water head is sufficient to cause intrusion; reversed flow is not required.

Because sea water intrusion represents displacement of miscible liquids in porous media, diffusion and hydrodynamic dispersion tend to mix the two fluids. The idealized interfacial surface becomes a transition zone. The thickness of the zone is highly variable; steady flows minimize the thickness, but nonsteady influences such as pumping, recharge, and tides increase the thickness. Measured thicknesses of transition zones range from a few feet in undeveloped sandy aquifers to hundreds of feet in overpumped basalt aquifers.

Flow within the transition zone varies from that of the fresh water body at the upper surface to near-zero at the lower surface. The movement in the transition zone transports salt to the ocean. Continuity considerations suggest that the salt discharge must come from the underlying sea water dispersing upward into the zone. It follows that there must be a landward sea water flow as sketched in Figure 1. This circulation has been verified by a field investigation at Miami, Florida (Cooper, et al, 1964).

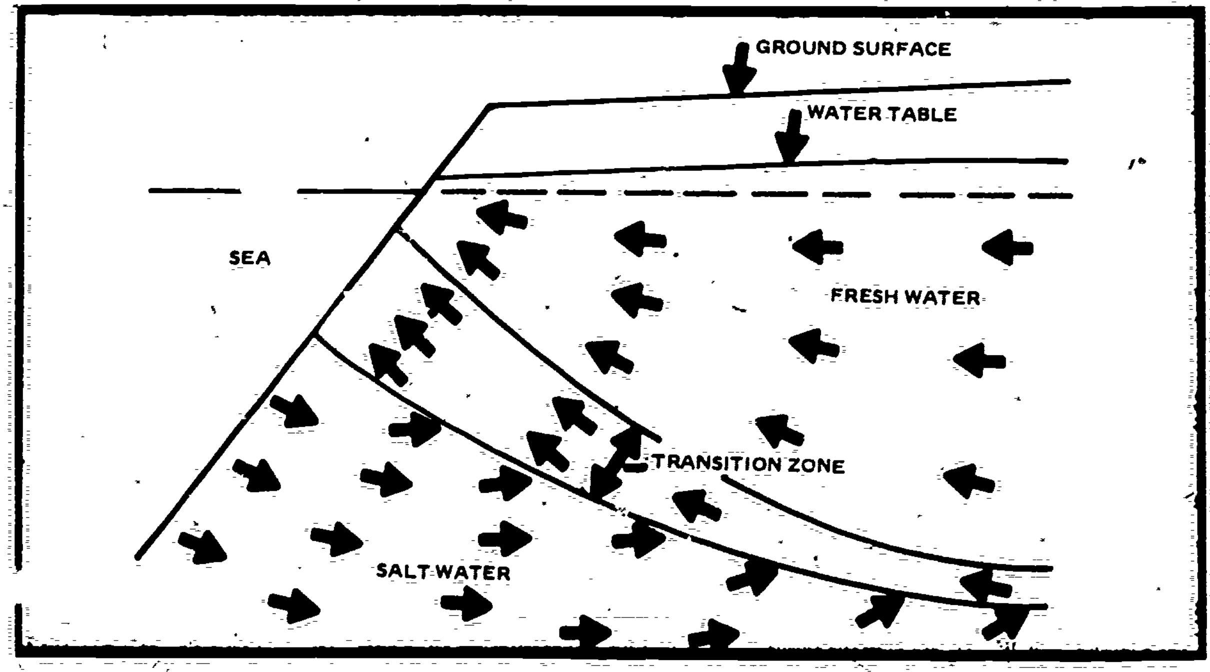

Figure 1. Schematic vertical cross section showing fresh water and sea water circulations with a transition zone.

Control Methods

A variety of methods have been proposed or utilized to control sea water intrusion.

Control of Pumping Patterns If pumping from a coastal ground water basin is reduced or relocated, ground water levels can be caused to rise. With an increased seaward hydraulic gradient, a partial recovery from sea water intrusion can be expected. Figure 2 illustrates the effect of moving pumping wells inland in a coastal confined aquifer.

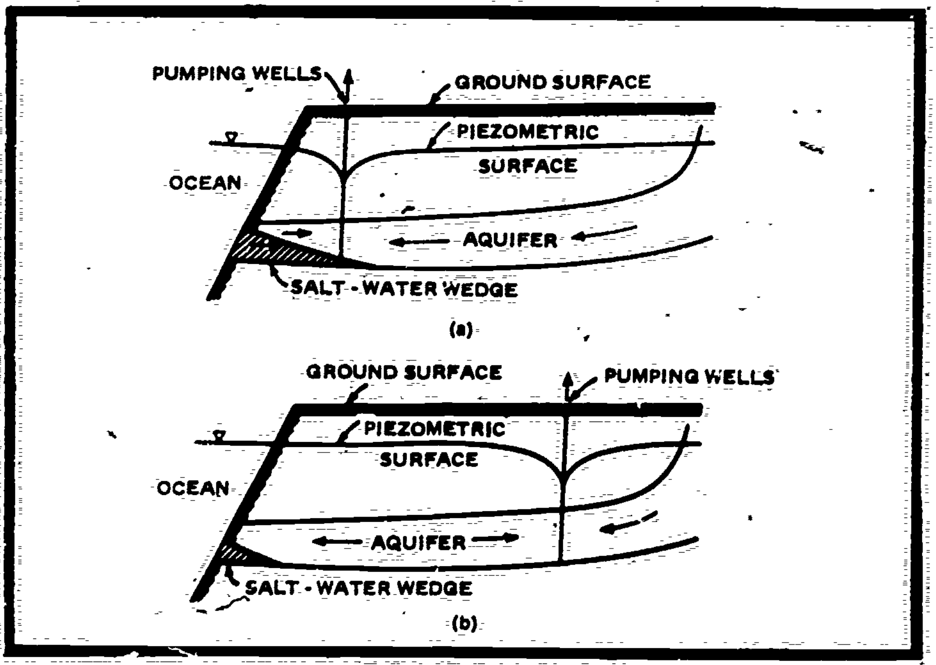

Figure 2. Control of sea water intrusion in a confined aquifer by shifting pumping wells from (a) near the coast to (b) an inland location (Todd, 1959).

<u>Artificial Recharge</u> Sea water intrusion can be controlled by artificially recharging an intruded aquifer by the use of surface spreading areas or recharge wells. By

offsetting potential overdrafts, water levels and gradients can be properly maintained. Spreading areas are most suitable for recharging unconfined aquifers, and recharge wells for confined aquifers.

Fresh Water Ridge Maintenance of a fresh water ridge in an aquifer paralleling the coast can create a hydraulic barrier which will prevent the intrusion of sea water. A line of surface spreading areas would be appropriate for an unconfined aquifer, whereas a line of recharge wells would be necessary for a confined aquifer. A schematic cross section of the flow conditions within a confined aquifer is shown in Figure 3. With a line of recharge wells paralleling the coast, the ridge would consist of a series of peaks and saddles in the piezometric surface. The required elevation of the saddles above sea level will govern the well spacing and recharge rates required. The ridge should be located inland of a saline front so as to avoid displacing the sea water farther inland. This control method has the advantage of not restricting the usable ground water storage capacity. The disadvantages are high installation and operational cost and the need for supplemental water which may be lost to the sea.

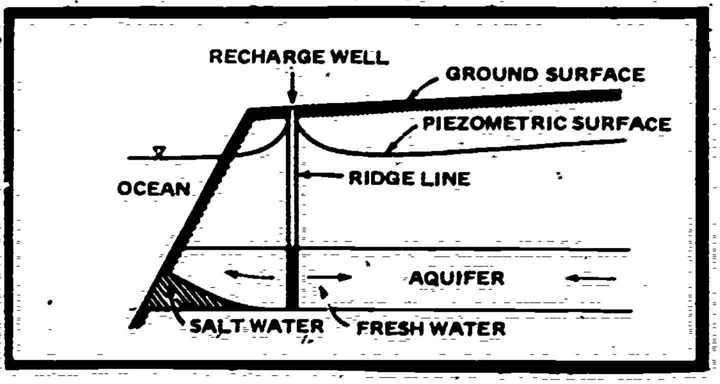

Figure 3 Control of sea water intrusion by a line of recharge wells to create a pressure ridge paralleling the coast (Todd, 1959).

Injection wells have been extensively and successfully employed along the Southern California coast. A new project underway in Orange County, California, will inject a combination of reclaimed wastewaters and desalted sea water (Cofer, 1972). Details of well construction are available in a report on the Los Angeles West Coast Basin barrier (McIlwain et al, 1970).

Extraction Barrier Reversing the ridge method, a line of wells may be constructed adjacent to and paralleling the coast and pumped to form a trough in the ground water level. Gradients can be created to limit sea water intrusion to a stationary wedge inland of the trough, such as illustrated in Figure 4 for a confined aquifer. This method reduces the usable storage capacity of the basin, is expensive, and wastes the mixture of sea and fresh waters pumped from the trough.

The trough method has been successfully tested at one location on the Southern California coast (California Department of Water Resources, 1970).

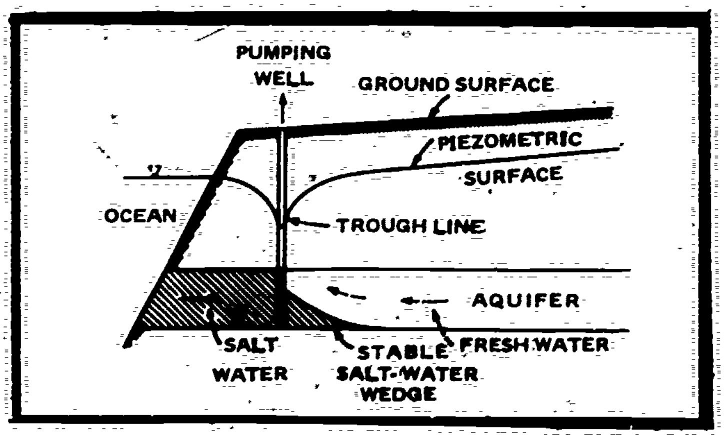

Figure 4 Control of sea water intrusion by a line of pumping wells creating a trough paralleling the coast (Todd, 1959).

Combination Injection-Extraction Barrier Using the last two methods, a combination injection ridge and pumping trough could be formed by two lines of wells along the coast. Figure 5 shows a schematic cross section of the method for a confined aquifer. Both extraction and recharge rates would be somewhat reduced over those required using either single method. The total number of wells required, however, would be substantially increased.

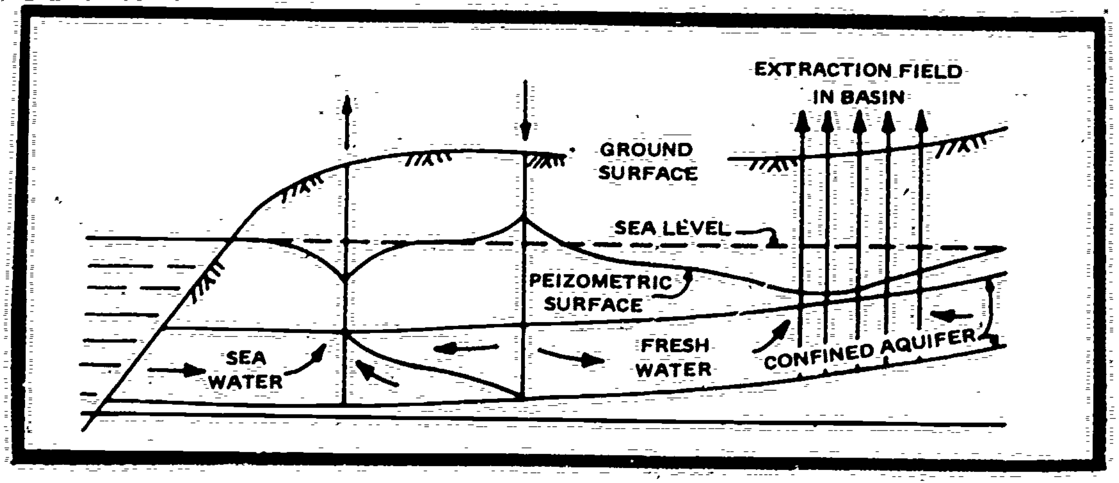

Figure 5 Control of sea water intrusion by a combination injection-extraction barrier using parallel lines of pumping and recharge wells (after California Department of Water Resources, 1966).

Subsurface Barrier By constructing an impermeable subsurface barrier through an aquifer and parallel to the coast, sea water would be prevented from entering the ground water basin. Figure 6 shows a sketch of such a barrier in a confined aquifer. A barrier could be built using sheet piling, puddled clay, emulsified asphalt, cement grout, bentonite, silica gel, calcium acrylate, or plastics. Leakage due to the corrosive action of sea water or to earthquakes would need to be considered in a barrier design. The method would prove most feasible in a narrow, shallow sinuous aquifer connecting with a larger inland aquifer. Although expensive, a barrier would permit full utilization of an aquifer.

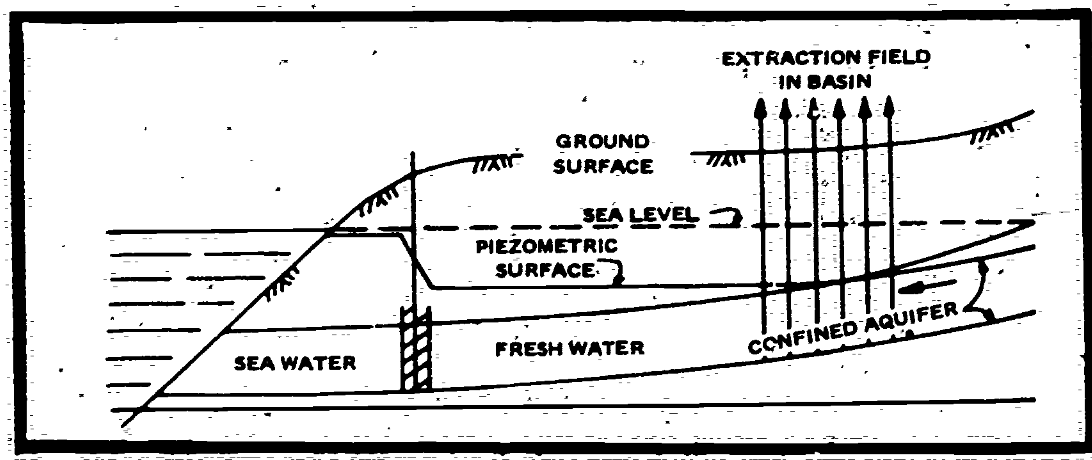

Figure 6 Control of sea water intrusion by construction of an impermeable subsurface barrier (after California Department of Water Resources, 1966).

Tide Gate Control Wherever drainage channels carry surplus waters from low-lying inland areas to the ocean, there is a danger of sea water penetrating inland during periods of high tides. If the channels are unlined, as is often the case, the sea water may immediately invade the adjoining shallow aquifers. To control such intrusion, tide gates should be installed at the outlet of each channel. These will permit drainage water to be discharged to the ocean but prevent sea water from advancing inland. This control method has operated successfully for many years in the Miami, Florida, area.

Monitoring Procedures

Whatever the method of sea water intrusion control adopted, a monitoring program will be a necessary part of the system. Conditions both within and outside of the intruded zone should be measured. Data will be required on ground water levels and chloride concentration. The vertical profile of the transition zone should be determined at a few key locations.

In general, observation wells should be located so as to provide a comprehensive picture of the local intrusion situation: along any line of control, on the seaward side, and on the landward side. The number of wells required can vary with individual circumstances; however, the fact that 30 observation wells were drilled for each mile of recharge line in the West Coast Basin of Los Angeles (McIlwain, et al, 1970) is indicative that a reasonably dense network may be required.

Observation wells should be measured for ground water levels and chloride concentration (or total dissolved solids) at intervals of one to two months under normal circumstances. Electrical conductivity logs should be run in selected wells on a similar frequency.

Most observation wells for the Los Angeles injection barrier were cased with 4-inch PVC plastic pipe in a gravel-packed and grouted 14-inch diameter hole (McIlwain, et al, 1970). For economic reasons multiple casings into as many as three aquifers were placed in the same drill hole. This required a 22-inch diameter drill hole with each of the gravel-packed casings grouted between the aquifers to prevent communiciation.

References

1. Ballentine, R.K., Reznek, S.R., Hall, C.W., Subsurface Pollution Problems in the United States, U.S. Environmental Protection Agency, Technical Studies Report TS-00-72-02, 1972.

2. Black, A.P., et al, Salt Water Intrusion in Florida - 1953, Water Survey & Research Paper No. 9, Florida State Board of Conservation, 38 pp (1953).

3. California Department of Water Resources, Sea-Water Intrusion in California, Bulletin 63, 91 pp plus appendices and supplements (1958).

4. California Department of Water Resources, Ground Water Basin Protection Projects; Santa Ana Gap Salinity Barrier, Orange County, Bulletin 147-1, 194 pp (1966).

5. California Department of Water Resources, Ground Water Basin Protection Projects; Oxnard Basin Experimental Extraction -Type Barrier, Bulletin 147-6, 157 pp. (1970).

6. Cofer, J.R., "Orange County Water District's Factory 21," Journal Irrigation and Drainage Division, American Society of Civil Engineers, Vol. 98, No. IR4, pp 553-467 (1972).

7. Cooper, H.H., Jr., et al, Sea Water in Coastal Aquifers, US Geological Survey Water-Supply Paper 1613-C, 84 pp (1964).

8. Louisiana Water Resources Research Institute, Salt-Water Encroachment into Aquifers, Bulletin 3, Louisiana State University, Baton Rouge, 192 pp (1968).

9. Luscynski, N.J., and Swarzenski, W.V., Salt-Water Encroachment in Southern Nassau and Southeastern Queens Counties, Long Island, New York, US Geological Survey Water-Supply Paper 1613-F, 76 pp (1966).

10. McIlwain, R.R., et al, West Coast Basin Barrier Project 1967-1969, Los Angeles County Flood Control District, Los Angeles, California, 30 pp plus appendices (1970).

11. Parker, G.G., et al, Water Resources of Southeastern Florida with Special Reference to Geology and Ground Water of the Miami Area, US Geological Survey Water-Supply Paper 1255, 965 pp (1955).

12. Pettit, B.M., Jr., and Winslow, A.G., Geology and Ground Water Resources of Galveston County, Texas, US Geological Survey Water-Supply Paper 1416, 157 pp (1957).

12. Shafer, G.H., Ground Water Resources of Aransas County, Texas, Texas Water Development Board Report 124, 1970.

13. Task Committee on Salt Water Intrusion, "Saltwater Intrusion in the United States," Journal of Hydraulics Division, American Society of Civil Engineers, Vol. 95. No. HY5, pp 1651-1669 (1969).

14. Todd, D.K., Ground Water Hydrology, John Wiley & Sons, New York pp 277-296 (1959).

15. Todd, D.K., "Salt Water Intrusion of Coastal Aquifers in the United States," International Association of Scientific Hydrology, Publication No. 52, pp 452-561 (1960).

16. Todd, D.K., and Meyer, C.F., "Hydrology and Geology of the Honolulu Aquifer," Journal of Hydraulics Division, American Society of Civil Engineers, Vol. 97, No. HY2, pp 233-256 (1971).

17. U.S. Environmental Protection Agency, Subsurface Water Pollution - A Selective Annotated Bibliography - Part II - Saline Water Intrusion, 1972.

18. Visher, F.N., and Minks, J.F., Ground Water Resources in Southern Oahu, Hawaii, US Geological Survey Water-Supply Paper 1778, 133 pp (1964).

UPSTREAM ENCROACHMENT OF SEA WATER

History and Scope of the Problem

Estuaries of large rivers have since ancient times offered convenient shelter for shipping and provided harbor locations for commerce inland and overseas. Associated structures and facilities remained of modest size until the relatively recent advent of deep-draft vessels which have necessitated extensive deepening of channels, and hence interference with the natural equilibrium between tidal currents and fresh water flow. The construction of canals in communication with estuaries or the sea has also served to conduct sea water inland. Other man-made changes in the upstream environment; control of fresh water flow for irrigation, water supply, hydro-power and flood control, and increased consumptive withdrawal of both surface and ground waters have served to decrease stream discharges alter the natural time sequence of hydrological events and further disrupt the natural equilibrium where the fresh water meets the sea.

This section briefly discusses the causal factors and pollutant movement associated with upstream encroachment of sea water and its environmental consequences. Thereafter, control methods and monitoring procedures are presented together with selected references to sources for more detailed information.

Encroachment in the United States

In the United States upstream migration of sea water is concentrated primarily on the East and Gulf Coasts but is also known on the West Coast. Nearly all of the coastal States between New Hampshire and Louisiana have had problems of this type. Streams of low gradients which are characteristic of the gently sloping coastal plain of this area require only moderate reductions in flow for sea water encroachment to take place. In recent years, during extended dry periods sea water has migrated up the Delaware River nearly as far as Philadelphia. Florida has had severe sea water encroachment problems caused by construction of drainage canals and channels; and harbor and channel dredging has increased the salt water encroachment problem in the Patapsco River in Maryland. These are but a few representative examples of numerous incidences of sea water encroachment along the East and Gulf Coasts.

Environmental Consequences

Upstream migration of the sea water wedge changes the salinity of aquatic environments and may render fish and wildlife habitats unsuitable for native populations. Sea water encroachment can contaminate human and agricultural water supplies necessitating costly treatment or relocation of intake points. Increased salinity in the upstream environment results in increased corrosion and shorter life expectancy for engineering structures. Because of the high salt content of sea water, exfiltration to the ground water from the advancing sea water wedge can contaminate fresh ground water supplies and leave them unsuitable for domestic purposes long after the encroaching wedge has migrated back down stream.

Causal Factors and Pollutant Movement

Upstream migration of sea water is generally the result of man's alteration of the hydraulic equilibrium that exists between the fresh water and sea water regimes. The most common causes of sea water encroachment in streams are dredging of navigation channels, construction of sea level canals, and reduction of stream flow.

Fresh water and sea water, being of different densities, when brought together under stable conditions tend not to coalesce but to form a distinct interface. Normally, maximum tidal velocities are much larger in the estuary portions of rivers than the mean velocities by which fresh water flow reaches the sea. The tidal velocities oscillate the salt water wedge back and forth with tidal stage and in doing so generate turbulent shear flows that cause mixing at the salt water/fresh water interface. If the tidal shear flows are weak and unable to overcome the stabilizing effects of the density difference between the sea water and the fresh water, a stratified condition with a very thin zone of mixing between the fresh water and the sea water results. If the shear flow induced by tidal action is sufficiently strong to overcome the stabilizing effects caused by the density difference between the two waters, increased mixing results and sea water encroachment is no longer characterized by a distinct interface but by a broad zone of mixing.

The interaction of river flow and tidal currents results in a net upstream bottom movement of sea water with fresh water overriding this wedge in a seaward direction. The position of the interface between the fresh water and sea water is dependent on channel geometry, river discharge, and high tide height. A change in any of these parameters will cause the salt water/fresh water interface to migrate. Reduction of stream flow or deepening of channels results in landward migration of the sea water wedge while increased stream flow results in a seaward migration.

Control Methods

Methods for control of sea water encroachment in streams rely on maintaining adequate fresh water flow or construction of physical barriers to prevent migration of the sea water landward. Maintenance of fresh water flow generally can not be achieved by any single technique, but requires basin wide management of withdrawal, recharge, and storage of both surface and ground waters. Since most surface streams receive part of their flow from the ground water reservoir during all or part of the year, any procedure that recharges the ground water system will also aid in maintaining stream flow and in retarding sea water encroachment. The primary elements of basin wide water management that aid in controlling sea water encroachment in streams include the following:

<u>Ground Water Recharge</u> The ground water reservoir can be thought of as the regulator of base stream flow. Much of the water that falls on the land percolates to the ground water reservoir and is slowly and steadily discharged to surface streams. If the ground water reservoir is depleted throu overdraft or impediment of natural recharge (e.. paving of large areas and diversion of precipitation to storm sewers) water is not available in the subsurface to maintain sufficient stream flow to prevent sea water encroachment during dry periods. Much of the water that runs

off during storms can be diverted to the subsurface by construction of recharge basins. This technique is particularly amenable to highway storm drainage and is thoroughly discussed in a report by Weaver (1971). The recharge of high quality waste waters such as cooling waters or tertiary treated sewage by the use of recharge wells or surface spreading also aids in maintaining the subsurface water supply. These techniques are discussed in the section on sea water intrusion into coastal aquifers.

<u>Surface Water Impoundment and Regulated Release</u> Stream flow can be regulated and sea water encroachment retarded by impounding excess surface waters during periods of high runoff and releasing these waters during periods of low stream flow. The economics of such projects and the large volumes of water required generally preclude their undertaking solely for sea water intrusion control. This contingency, however, should be incorporated in plans for impoundment structures for flood control, irrigation, and recreation.

Tide Gates and Locks Where channels with low gradients meet the sea there is always a danger of sea water encroachment during periods of high tide and low flow. The installation of tide gates for control of such encroachment is discussed in the section on sea water intrusion into coastal aquifers. Sea water can also migrate upstream through navigation locks in shipping canals wher water is taken into the locks from the seaward side and released on the landward side. This type of sea water encroachment can be reduced or eliminated by controlled filling and emptying of the locks. These techniques are discussed in reports by Blanchet and Quetin (1972) and Bogges (1970).

Monitoring Procedures

A monitoring program should be an integral part of any program for control of sea water encroachment. Monitoring should be sufficient to determine the location and geometry of the salt water/fresh water interface at any time and to relate movement of the interface to the causal factors. In general, monitoring points should be located on the landward side of locks and tide gates and near the mouths of tidal channels to give a longitudinal profile of salt concentrations in the upstream direction. The number of monitoring points required will vary with local conditions and extent of sea water encroachment. Monitoring points should be measured for chloride levels (or total dissolved solids) at monthly intervals during normal conditions and more frequently when sea water is actively encroaching.

References

1. Blanchet, Ch. and Quetin B., "Mardyck Locks as Salt-Water Barrier", Journal of the Waterways, Harbors, and Coastal Engineering Division, ASCE, Vol. 98, No. WW4, Proc. Paper 9387, Nov. 1972, pp. 561-567.

2. Boggess, Durward H., A Test of Flushing Procedures to Control Salt Water Intrusion at the W. P. Franklin Dam Near Ft. Myers, Florida, Information Circular No. 62, State of Florida Department of Natural Resources, 1970.

3. Weaver, Robert J., Recharge Basins for Disposal of Highway Storm Drainage, Research Report 69-2, Engineering Research and Development Bureau, New York State Department of Transportation, May 1971.

4. Ippen, Arthur T., "Salt-Water Fresh-Water Relationships in Tidal Channels", Proc. Second Annual Am. Water Res. Conf. pp 47-55, Nov. 22, 1966.

5. Owen, Langdon W., "Salinity Intrusion and Related Studies Sacramento - San Joaquin Delta", International Commission on Irrigation and Drainage,, Vol. 4 pp. 21.15 - 21.35, 1966.

SALINE WATER IN INLAND AQUIFERS

Scope of the Problem

Hydrologic data accumulated in recent years indicate that large quantities of saline water exist under diverse geologic and hydrologic environments in the United States. Most of the nation's largest inland sources of fresh ground water are in close proximity to natural bodies of saline ground water.

Saline water is an inherent constituent of marine-derived sedimentary rocks which form some significant aquifers exploited today. Waters with high natural mineral content can be found at relatively shallow depths throughout large portions of the United States. Fresh water recharge has flushed much of the saline water from many aquifers throughout geologic time. Saline water may remain at depth or where exposure to fresh water recharge has not occurred. Brines occur in almost all areas at the depths explored and developed by the oil industry.

According to the Task Committee on Salt Water Intrusion, 1969, saline water in inland aquifers may be derived from one or more of the following sources:

Sea water which entered aquifers during deposition or during a high stand of the sea in past geologic time

Salt in salt domes, thin beds, or disseminated in the geologic formations,

Slightly saline water concentrated by evaporation in playas or other enclosed areas,

Return flows from irrigated lands,

Man's saline wastes.

When development of an aquifer by acts of man causes saline water from any of these sources to move into the fresh water aquifer, salt water intrusion results.

Intrusion in the United States

Considerable information exists on the geographic distribution of saline ground water (here defined as water containing more that 1,000 mg/l dissolved solids) (Feth, 1965; Feth, et al, 1965; Task Committee on Salt Water Intrusion, 1969). These reports indicate that approximately two-thirds of the conterminous United States is underlain in part by saline ground water.

In the Atlantic and Gulf Coastal Plain and in many ground water basins on the Pacific Coast, saline water occurs because of sea water that was trapped in the sediments during deposition (connate water) or that invaded the sediments during previous high stands of the sea.

In the Midwest, bedrock aquifers generally contain mineralized water at depths below about 122 meters. Aquifers with saline waters of more than 1,000 mg/l dissolved solids underlie fresh-water aquifers throughout most of the Great Plains area from central Texas to Canada. In the mountainous area from the Rocky Mountains to the

Pacific Coast, saline water occurs at depth in many ground water basins.

Environmental Consequences

Intruded fresh-water aquifers typically are locally affected. Because of the relatively slow movement of ground water, saline water intrusion may produce detrimental effects on ground water quality that could persist for months under the most favorable circumstances, or many years or decades in other cases.

Causal Factors

Salt water intrusion can result from several mechanisms. One involves the upward movement of saline water through the aquifer as a result of some act of man on the hydrologic regime, such as overpumping. Another occurs by saline water moving vertically through wells into a fresh-water aquifer. Saline water intrusion also can occur where construction of a waterway or channel involves removal of materials which have acted as an impermeable blanket between saline waters and fresh-water aquifers. Destruction of natural barriers may also permit saline water on the surface to be carried past natural geologic barriers, such as faults which previously protected the fresh-water aquifer.

Pumping of an aquifer underlain by saline water will cause the ground water level to be lowered, which in turn can cause an upconing of the saline water into the aquifer and eventually the well itself. Figure 7 shows the sequence of upconing to a pumping well in an unconfined aquifer.

Where saline and fresh-water aquifers are connected hydraulically, dewatering operations, as for quarries, roads, or excavations, may cause vertical migration of saline water. Similarly, the deepening or dredging of a gaining stream will cause a lowering of the head in the aquifer near the stream. If the aquifer is hydraulically connected to an underlying saline aquifer, the lowering of head will induce upward movement of saline water. Figure 8 illustrates the zone of saline water intrusion produced when a water table is lowered. This indicates that encroachment of saline water can be a potential problem where flood control or other projects modify stream stages.

Extensive pollution of fresh water aquifers has been caused by vertical leakage of saline water through inactive or abandoned wells or test holes. A well is an avenue of nearly infinite vertical permeability through which saline water may move. Pumping from fresh-water aquifers may lower water tables below the piezometric surfaces of lower saline water zones. Examples of saline water moving upward into a fresh-water aquifer through various types of wells are sketched in Figure 9.

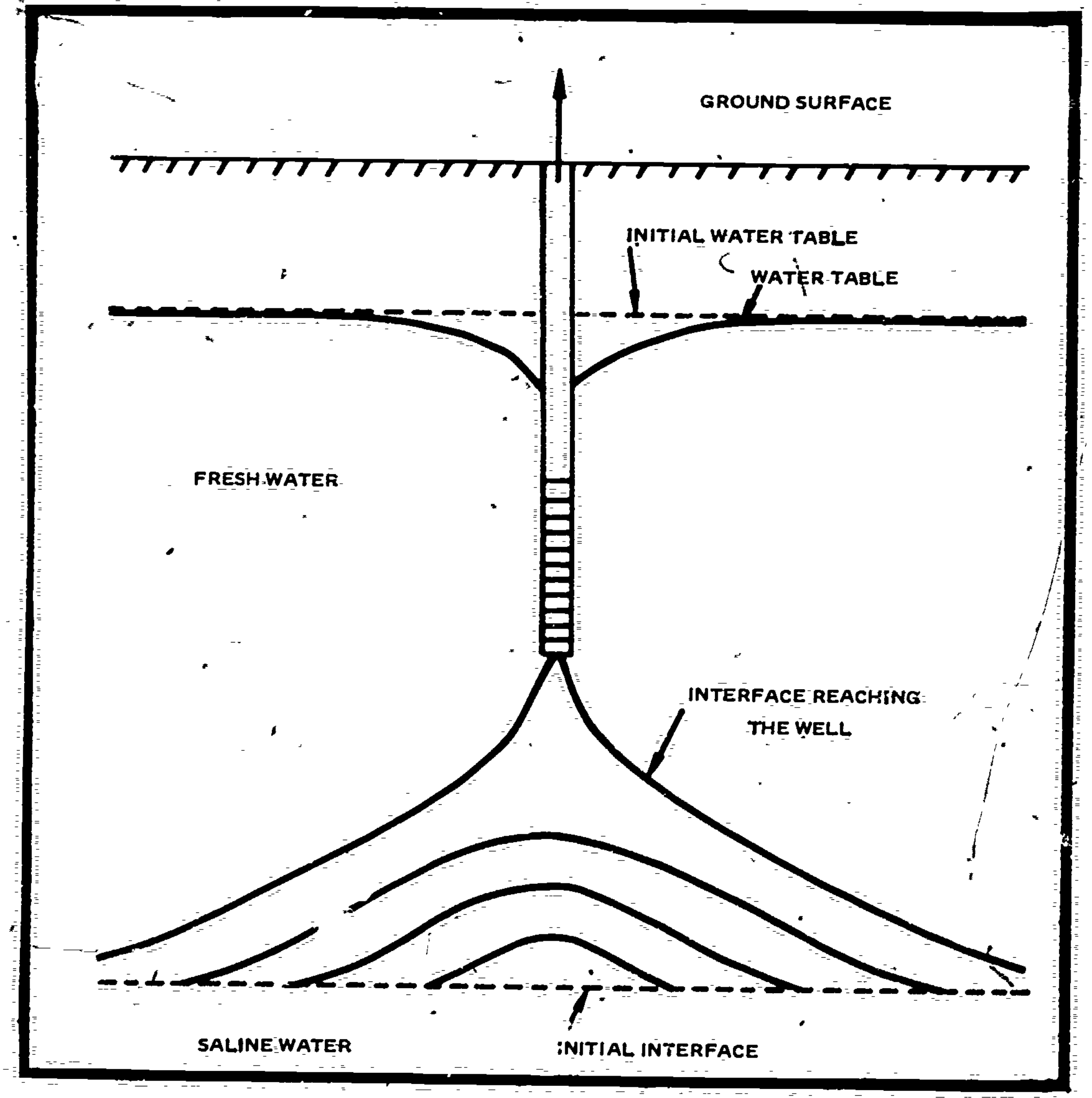

Figure 7 Schematic diagram of upconing of underlying saline water to a pumping well.

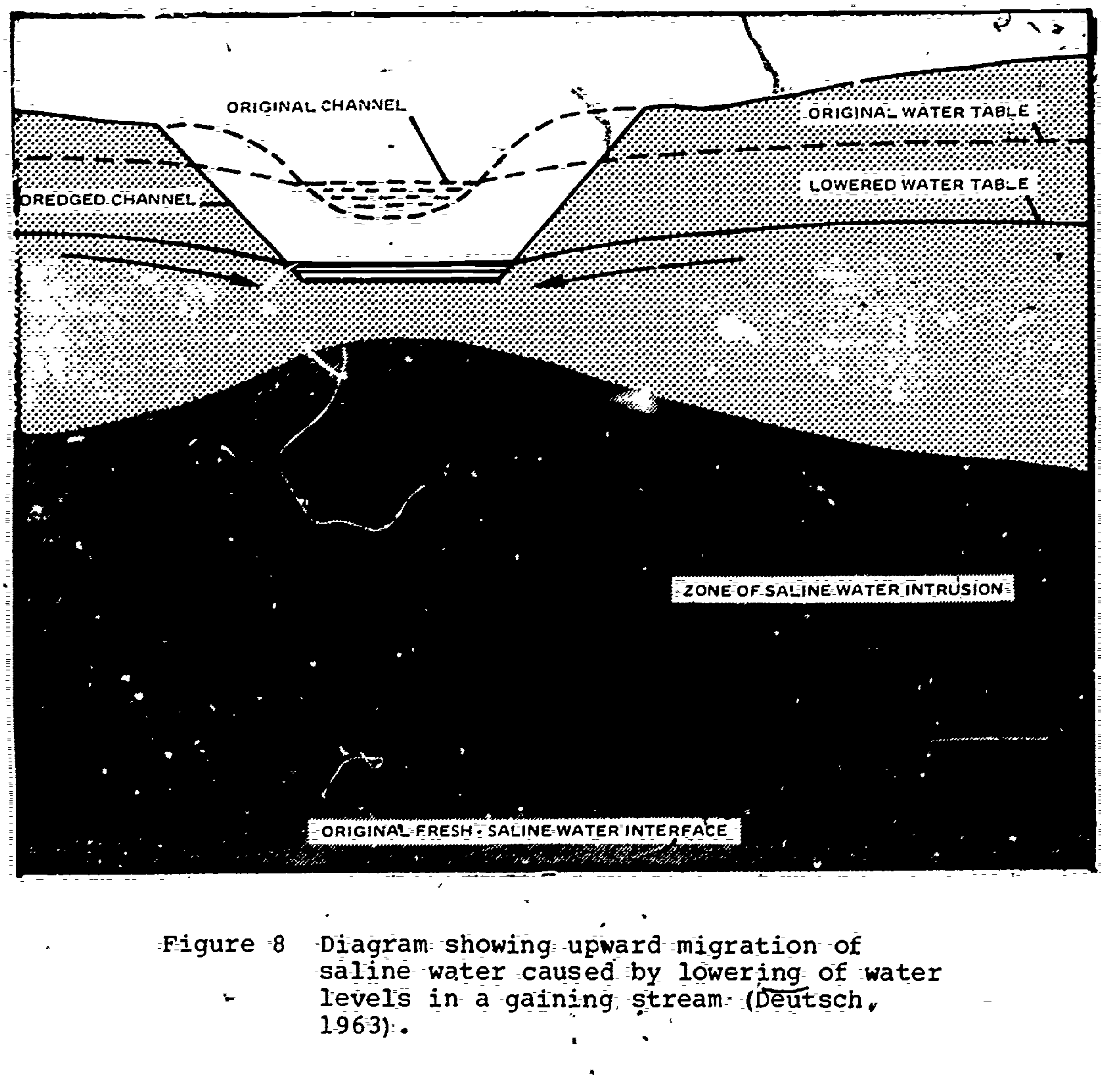

Figure 8 Diagram showing upward migration of saline water caused by lowering of water levels in a gaining stream (Deutsch, 1963).

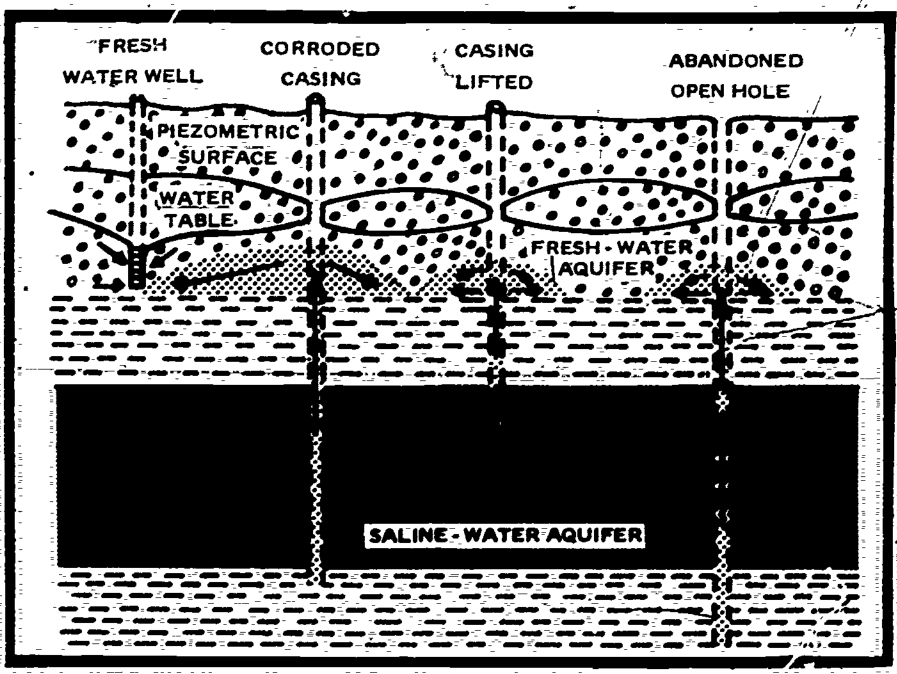

Figure 9 Diagram showing interformational leakage by vertical movement of water through wells where the piezometric surface lies above the water table (after Deutsch, 1963).

Indicative of all of the above mechanisms is the intrusion situation in Southern Alameda County, California, shown in Figure 10. Here a combination of four causal factors - natural and man-made - has lead to intrusion in two distinct aquifers. Although the intruding water shown here is sea water, the mechanisms apply equally to any saline water source.

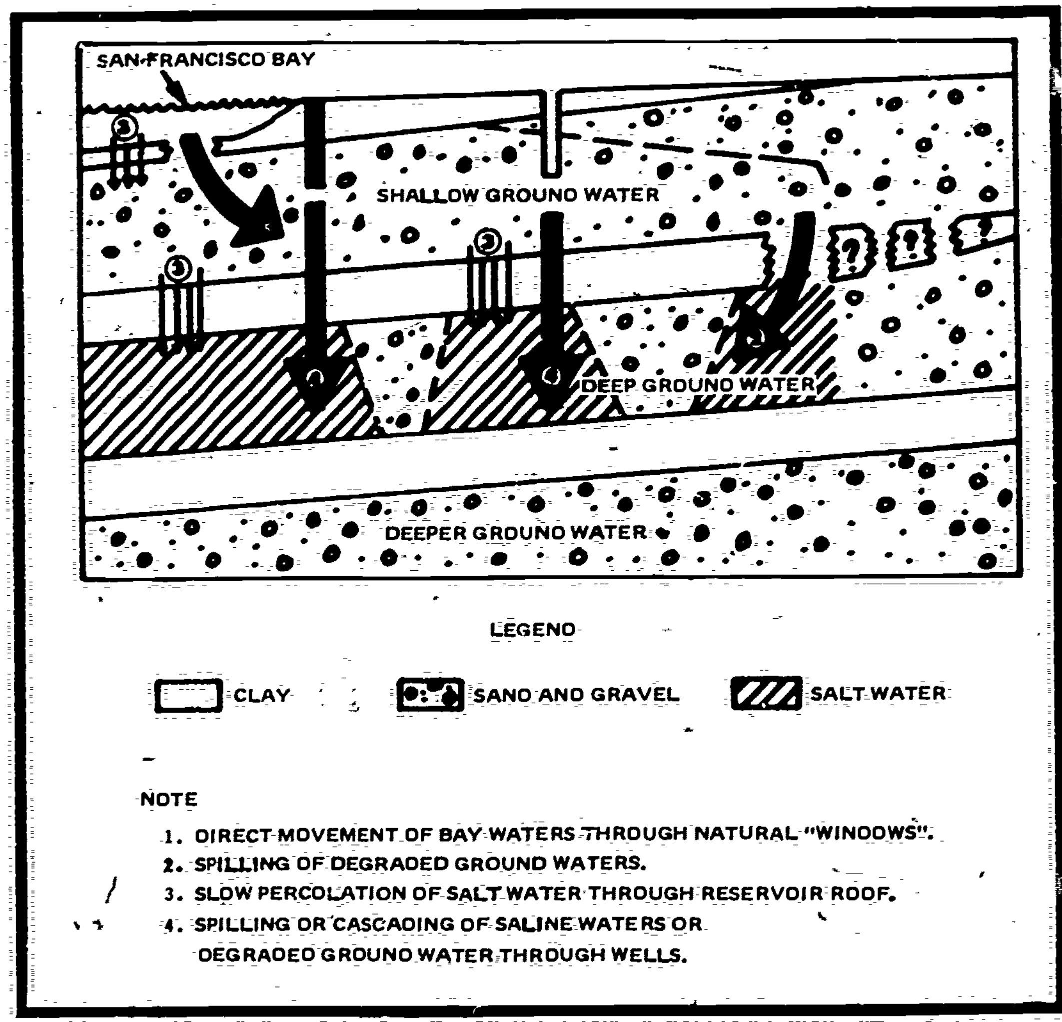

Figure 10 Illustrative sketch showing four mechanisms producing saline water intrusion in Southern Alameda County, California (after California Department of Water Resources, 1960).

Pollutant Movement

When an aquifer contains an underlying layer of saline water and is pumped by a well penetrating only the upper fresh water portion, a local rise of the interface below the well occurs. With continued pumping this upconing rises to successively higher levels until eventually it may reach the well. When pumping is stopped, the denser saline water tends to subside to its original position.

The factors governing upconing include the pumping rate of the well, the distance between the well and the saline water, the duration of pumping, the permeability of the aquifer, and the density difference between the fresh and saline waters.

Upconing is a complex phenomenon. Quantitative criteria have been formulated for the design and operation of wells for skimming fresh water from above saline water (Schmorak and Mercado, 1969). From a water-supply standpoint it is important to determine the optimum location, depth, spacing, pumping rate, and pumping sequence to maximize production of fresh ground water while minimizing the undermixing of fresh and saline waters.

The movement of saline water within wells is in the direction of the hydraulic gradient. The flow can occur either upward or downward, depending upon the direction of the head differential. Also, head differences may result from natural geologic causes or from effects of pumping. Typically, a well pumping from a fresh-water zone reduces the head there to a value lower than that of other zones. If the non-pumped zones contain saline water and are connected hydraulically to the well, intrusion into the fresh-water zone will result.

Control Methods

A variety of methods are available to control saline water intrusion in aquifers. The selection of a particular method will depend on the local circumstances responsible for the intrusion. Alternative control methods are briefly described in the following subsections.

Reduced Pumping Where pumping of a fresh-water aquifer produces upconing of saline water, an effective control method is to reduce pumping. This may take the form of actual termination of pumping, of reduction in the pumping rate from individual wells, or of the decentralization of wells. The more pumpage is reduced, the greater the tendency for the saline water interface to subside and to form a horizontal surface.

Illustrative of the consequences of pumping rate are data shown in Figure 11 from the Honolulu aquifer. Here underlying saline water (actually sea water) in a nearby observation well moves upward and downward in accordance with the pumping rate of a well.

<u>Increased Ground Water Levels</u> In situations where surface construction or excavations have lowered ground water levels and caused underlying saline ground water to rise (see Figure 8), any action which raises the ground water level will be effective in suppressing intrusion. Artificial recharge of an unconfined aquifer, for example, would have a beneficial effect. Similarly, raising surface water levels, as by regulating stream stages or by releasing water into surface excavations, will cause a corresponding upward adjustment in the adjacent water table.

__Protective__ __Pumping__ Because saline water moves into a fresh water aquifer under the influence of a pressure gradient, an effective control method is to reduce the pressure in the saline water zone. This can be accomplished by drilling and pumping a well perforated only in the saline water portion of the aquifer. Although the water pumped is saline and may present a disposal problem, this method does permit the continued utilization of the underground fresh water resources without increasing intrusion. The method was successfully applied to counteract a growing intrusion problem in Brunswick, Georgia (Gregg, 1971).

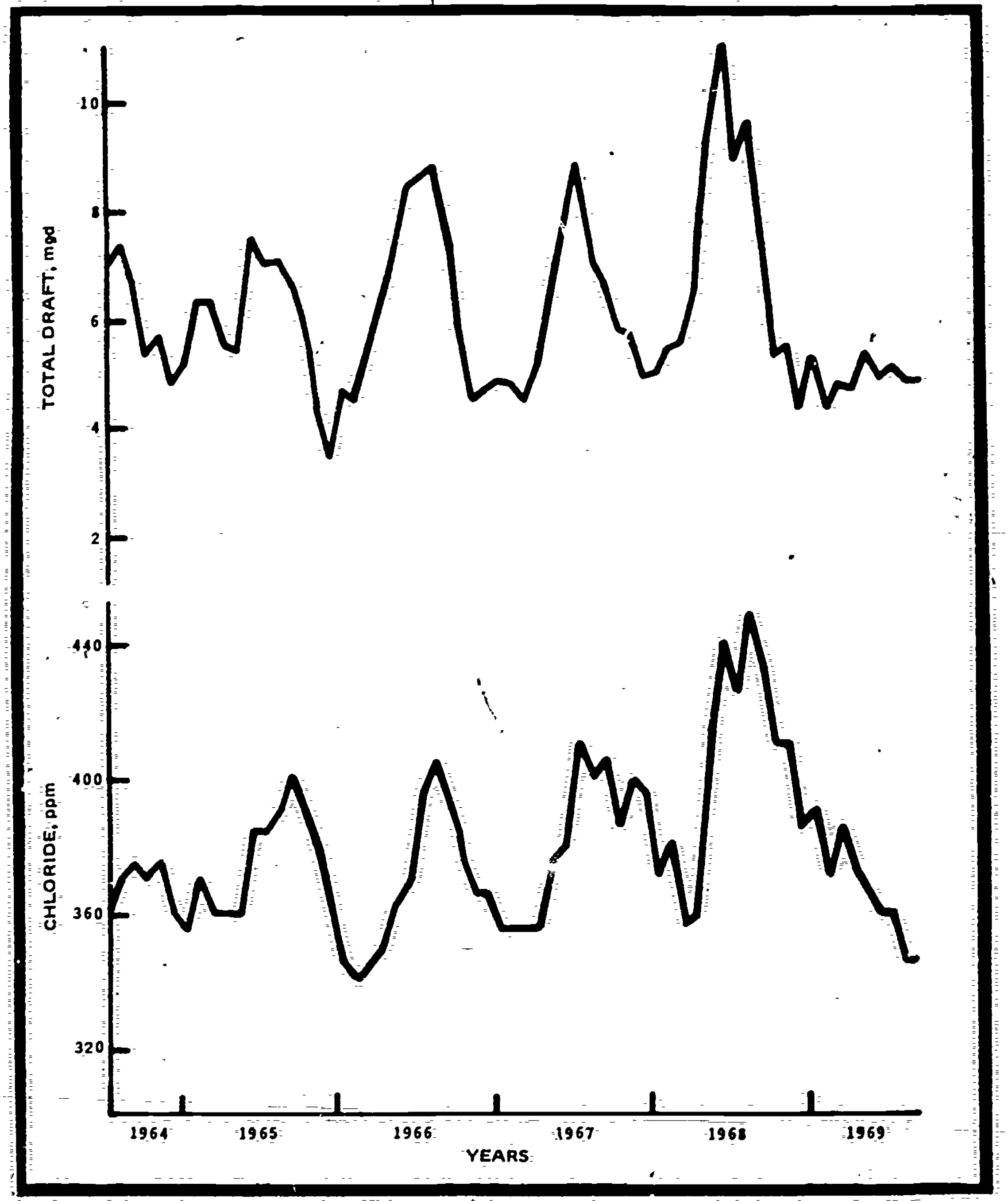

Figure 11 Monthly variations of total draft and chloride content in a nearby observation well, Honolulu aquifer (after Todd and Meyer, 1971).

Sealing Wells To minimize the vertical movement of saline water in abandoned wells and test holes, they should be completely sealed by backfilling with an impermeable material. Dumping of loose soil into a well seldom provides an effective guarantee of impermeability, particularly in a deep well. One method is to pump a cement slurry into the well, filling from the bottom upward. The material will then create a void-free column having a lower permeability than that of the surrounding formations.

Well Construction To control the movement of saline water within active wells that are either pumping or resting requires careful well construction. During the drilling of a well, one or more zones of saline water may be encountered. When the full depth of the well has been reached, those formations expected to be developed for fresh water production are selected. Perforations should be placed only opposite the fresh-water zones. Unperforated casing should be placed opposite saline water strata, with the annulus outside of the casing carefully sealed to isolate saline zones from the fresh-water zone. Details of well construction are available in standard references (Campbell and Lehr, 1973; Gibson and Singer, 1971; Todd, 1959).

Monitoring Procedures

When fresh-water aquifers need to be protected against vertical intrusion, a monitoring network to verify the effectiveness of the control method should be installed. In general, the network will consist of observation wells perforated within the fresh-water zone and sampled regularly for total dissolved solids or electrical conductivity. The monitoring wells should be in the deepest portions of the fresh-water zone so as to reveal the first evidence of intrusion, and spaced close enough to pumping wells that upconing will be detected. Periodic checks should also be made to ascertain that any newly abondoned wells or test holes are properly sealed and long abandoned wells that are identified through records search or other means should be located and plugged. Regular measurements of pumping rates and ground water level fluctuations, both natural and artifically produced, will help to recognize causal factors responsible for actual or incipient intrusion problems.

References

1. Ballentine, R.K., Reznek, S.R., Hall, C.W., Subsurface Pollution Problems in the United States, U.S. Environmental Protection Agency Technical Studies Report TS-00-72-02, 1972.

2. California Department of Water Resources, Intrusion of Salt Water into Ground Water Basins of Southern Alameda County, Bulletin 81, 44 pp (1960).

3. Campbell, M.D., and Lehr, J.H., Water Well Technology, McGraw-Hill, New York, 681 pp (1973).

4. Deutsch, M., Ground Water Contamination and Legal Controls in Michigan, US Geological Survey Water-Supply Paper 1691, 79 pp (1963).

5. Feth, J.H., Selected References on Saline Ground Water Resources of the United States, US Geological Survey Circular 499, 30 pp (1965).

6. Feth, J.H., et al, Preliminary Map of the Conterminous United States Showing Depth to and Quality of Shallowest Ground Water Containing More than 1000 Parts Per Million Dissolved Solids, US Geological Survey Hydrologic Invests. Atlas HA-199 (1965).

7. Gibson, U.P., and Singer, R.D., Water Well Manual, Premier Press, Berkeley, California, 156 pp (1971).

8. Gregg, D.O., "Protective Pumping to Reduce Aquifer Pollution, Glynn County, Georgia", Ground Water, Vol. 9, No. 5, pp 21-29 (1971).

9. Schmorak, S., and Mercado, A., "Upconing of Fresh Water-Sea Water Interface Below Pumping Wells, Field Study", Water Resources Research, Vol. 5, No. 6, pp 1290-1311 (1969).

10. Task Committee on Salt Water Intrusion, "Salt Water Intrusion in the United States", Journal of Hydraulics Division, American Society of Civil Engineers, Vol. 95, No. HY5, pp 1651-1669 (1969).

11. Todd, D.K., Ground Water Hydrology, John Wiley & Sons, New York, pp 115-148 (1959).

12. Todd, D.K., and Meyer, C.F., "Hydrology and Geology of the Honolulu Aquifer", Journal of Hydraulics Division, American Society of Civil Engineers, Vol. 97, No. HY2, pp 233-256 (1971).

13. U.S. Environmental Protection Agency, Subsurface Water Pollution - A Selective Annotated Bibliography - Part II - Saline Water Intrusion, 1972.

14. Winslow, A.G., and Doyel, W.W., Salt Water and Its Relation to Fresh Ground Water in Harris County, Texas, Texas Board of Water Engineers, Bulletin 5409, 37 pp (1954).

INSTITUTIONAL AND LEGAL ASPECTS

The Federal Water Pollution Control Act As Amended

The Federal Water Pollution Control Act as Amended recognizes, as a policy of the Congress, the primary responsibility of the States to prevent, reduce, and eliminate water pollution. The Adminisitrator of EPA is directed to develop comprehensive programs for water pollution control in cooperation with State and local agencies and with other Federal agencies. Thus, the laws and institutions relating to water, and their adequacy, are of basic importance. In most states, the functions of administration of water rights and of water pollution control are the responsibility of different state agencies.

Water Rights

Any attempt to control an activity involving the diversion and use of surface or ground waters, in order to prevent water pollution, will probably involve vested water rights and usually will be in conflict with these water rights. For many streams, ground water basins, and aquifers throughout the United States, rights to the full yield have long since been vested, either through actual diversion and use, or because of the riparian status of lands or ownership of overlying lands, even though no use of water is being or has been made.

There is little question that the Federal Government has the constitutional power to control the use of most of the surface waters of the United States. Under the reservation doctrine, confirmed by the United States Supreme Court in Arizona vs California, 373 US 546 (1963), the Federal Government can control and use the waters originating on or flowing across reserved or withdrawn public lands. A large proportion of the natural runoff of the western states originates on such lands, under the jurisdiction of the US Forest Service, the National Park Service, and other Federal agencies. The federal power to control navigable waters has long been established and confirmed by a series of US Supreme Court decisions. The Court definitions of what constitutes navigable waters are broad enough to encompass nearly all surface streams of any significant magnitude and their tributaries (United States vs Grand River Dam Authority, 363 US 229, 1960).

The Federal Government has never elected to assert these constitutional powers over surface waters in a general manner except with respect to control of pollution resulting from disposal of wastes. Rather, the Congress has repeatedly stated that the states shall control the use of intrastate waters. Section 8 of the Reclamation Act of 1902 (32 Stat. 388, 1902) explicitly provides that the Secretary of the Interior shall obtain water rights for reclamation projects in accordance with state water laws. The same provision or one expressing the same intent has been included in acts amendatory of and supplementary to the original Reclamation Act, and in numerous other enactments concerning water resources, including the Flood Control Act of 1944 (58 Stat. 887, 1944).

In further support of this apparently consistent Congressional intent, it is significant that there are no federal statutes governing the allocation of water resources, surface or ground, or the administration of water rights. Although periodically bills are introduced in Congress for those purposes, they have never passed beyond the committee stage. Up to 1973, therefore, responsibility for the allocation of water resources and the granting and administration of rights to intrastate waters has been left to the states. Interstate compacts have been executed for many of the more significant interstate streams systems. Some of these (the Delaware River Basin Compact, for example) encompass the associated interstate aquifers. To date, federal power over ground water resources has been asserted only in specific instances involving water supplies for federal installations (State of Nevada vs United States, 165 F. Supp. 600, 1958). Indian water rights, now almost entirely unquantified, and apparently definable only by individual actions brought before the US Supreme Court, are becoming highly controversial and becloud the entire water rights situation over much of the United States. For surface waters, the riparian doctrine of water rights is followed in several of the eastern, southern, and midwestern states; only Florida, Indiana, Iowa, Minnesota, Mississippi, New Jersey, and Wisconsin have strong statutes governing the diversion and use of such waters. In other states, the appropriation doctrine is followed, and the right to divert and use surface water must be acquired in accordance with state law. Most of these state laws are based on the objective of maximizing the economic beneficial uses for municipal and industrial water supply, irrigation, power production, and the like. With but few exceptions (eg, California) state water rights laws do not provide adequately for water quality control and in-stream uses such as for fish and wildlife resources. Generally, the hydrologic and hydraulic interrelationships of surface waters and ground waters are not recognized in state water laws.

Some states (Colorado, Florida, Indiana, Iowa, Minnesota, Nevada, New Jersey, New Mexico, and Utah) have statutes governing the extraction and use of ground water. The State Water Resources Control Board of California has only the power to initiate an adjudicatory action in the courts; imposition of a physical solution depends upon a finding that such action is necessary to prevent destruction of or irreparable damage to the quality of ground waters (Sec. 2100 et seq, Water Code). Most ground water laws have been laid down by the courts and vary widely from state to state. In California, for example, the courts follow the correlative doctrine, whereas in Texas, the courts have consistently followed the doctrine of absolute ownership or the rule of capture (City of Corpus Christi vs City of Pleasanton, et al, 154 Tex. 289, 276 S.W. 2d 798, 1955).

Under the later doctrine, it is impossible to control the extraction and use of ground water in any significant way, although certain limited powers to control well spacing, thus affecting extraction rates, are granted to underground water conservation districts formed in a few areas of the state (Chap. 52, Texas Water Code).

Present state statutes and case law concerning the rights to the use of water are completely inadequate to control the pollution of ground water that might result from the diversion and use of either surface or ground water. State laws need to be revised and broadened, as has been recommended by the National Water Commission (1972).

Ground Water Basin Management

Concept

The concept of managing a ground water basin is analogous to the operation of a surface water reservoir. By regulating the releases of water from a dam, the reservoir can be made to serve various beneficial purposes, and with planning the benefits can be optimized. In general, the benefits depend not on maintaining the reservoir full or empty at all time but rather on varying the water level to meet predetermined supply and demand criteria.

Ground water basins are increasingly being recognized as important resources for water storage and distribution. Ground water reservoirs have numerous advantages over surface reservoirs: Initial costs for storage are essentially zero, siltation is not a problem, eutrophication is not a problem, water temperatures and mineral quality are relatively uniform, evaporation losses are negligible, turbidity is generally insignificant, no land surface area is required, and useful lives are often idefinite.

The objective of ground water basin management is generally to provide an optimal continuing supply of ground water of satisfactory quality at minimum cost. To reach this objective requires comprehensive geologic and hydrologic investigations , development of a model to simulate the aquifers, economic analyses of alternative operational schemes, and finally, based on this management study, regulation of the basin. In most cases conjunctive use of surface water and ground water systems is considered in seeking a maximum water supply at minimum cost (Todd, 1959).

Procedure

The management study leading to a basin operation consists of the components listed below. These are arranged to indicate the usual sequential order employed.

Geologic Phase

- Data collection and water level maps
- Storage capacity and change; transmission characteristics
- Water quality analysis

Hydrologic Phase

- Data collection
- Base period determination
- Water demand
- Water supply and consumptive use
- Hydrologic balance

Mathematical Model

- Programming and parameter development
- Validation

Operation-Economic Phase

- Future water demand and deep-percolation criteria
- Analysis of cost of facilities
- Cost-of-water study
- Plans of operation
- Cost comparision of plans

Preparation of Report

Physically, the management of a basin involves regulating the patterns and schedules of recharge and extractions of water. This would include specifying the number and location of wells together with their pumping rates and annual limitations on total extractions. The upper and lower ground water levels would be defined. Water quality objectives would be set, and sources and causes of pollution carefully controlled. The artificial recharge of storm flows, imported water, or reclaimed water could be involved. In some instances, measures to limit sea water intrusion and land subsidence would be included.

Because of the dynamic nature of ground water resource systems, a continuing data collection program is essential. Management parameters and criteria must be re-evaluated at intervals of five to ten years.

Detailed management studies for several basins in California have been undertaken (Calif. Dept. of Water Resources, 1968).

Sources of Basin Pollution

Within a ground water basin the potential sources of pollution may include all of the possibilities previously described as well as many others. A pollution source unique to basin management may be artificial recharge of ground water. In order to increase the available ground water supply, a basin may be heavily pumped so as to lower ground water levels. Thereafter, water can be artificially and naturally recharged to fill the available underground storage space. Recharging is usually accomplished by surface spreading in which water is released for infiltration into the ground from basins, ditches, streambeds, or irrigated lands (Muckel, 1959). Water can also be recharged into confined aquifers through injection wells. If the quality of the recharged water is inferior to that of the existing ground water, pollution will result.

An excellent illustration is the situation in Orange County, California (Moreland and Singer, 1969). To compensate for extensive overdraft of the ground water basin during the 1940's, large quantities of imported Colorado River water were subsequently recharged underground along the Santa Ana River channel. Because of the high salt content of the imported water, the salintiy of a substantial portion of Orange County's ground water has been significantly increased.

On a long-range basis, maintenance of salt balance in a basin, i.e., prevention of accumulation of salts, must be achieved. This is the most difficult quality-maintenance problem.

Control Methods

Proper management o_ a ground water basin requires an appropriate institutional structure embracing the basin to insure that the water quality is not adversely affected. Control methods could include the following:

Maintaining ground water levels below some shallow depth so as to minimize the opportunity for pollution from surface sources.

Maintaining ground water levels above some greater depth in order to avoid upward movement of more saline and warmer water into the aquifer.

Regulating the quality of water artificially recharged to the aquifers. Storm runoff collected in upstream reservoirs and then released into spreading areas is usually of higher quality than ground water, but imported and reclaimed water may not be.

Preventing sea water intrusion and the inflow of poor-quality natural waters from adjacent surface and subsurface sources. Poor-quality water from underground sources can usually be excluded by lines of pumping or recharge wells, while surface waters can be intercepted by drainage ditches and diverted from the basin.

Regulating the drilling, completion, and operation of all types of wells.

Regulating land use over the basin to prevent the development of sources of ground water pollution.

Reducing salt loads by exporting saline ground waters, wastewaters, or brines from desalted water supplies.

Monitoring the quality of ground water throughout the basin to identify and to locate any pollution sources and to verify corrective measures.

Legal and Institutional Requirements

Ground water management is not explicitly mentioned in the Federal Water Pollution Control Act as Amended, but is essential if the maximum overall benefit is to be derived from development and use of the underground resources, while at the same time protecting and maintaining ground water quality. The many interrelated sources and causes of ground water pollution and the inherent complexity of ground water resource systems make it mandatory that the problem of pollution control be approached on a "systems" basis through management, if control is to be effective.

Ground water management may be defined as the development and utilization of the underground resources (water, storage capacity and transmission capacity), frequently in conjunction with surface resources, in a rational and hopefully optimal manner to achieve defined and accepted water resource development objectives. Quality as well as quantity must be considered. The surface water resources involved may include imported and reclaimed water as well as tributary streams.

Generally, management can be most effectively accomplished at the local or regional governmental level, operating within a framework of powers and duties established by state statutes. A few such local management agencies with adequate powers have been formed and are operating; an example is the Orange County Water District, California (Orange County Water District Act, as amended).

Except for California, there are few, if any, state statutes under which effective management agencies can be established and operated. Current statutes and case law concerning water rights impede, and in some cases block, effective management. Principal weaknesses in the present legal and institutional posture at the state level with regard to control of ground water pollution from sources and causes other than waste disposal stem from these basic points:

In most states, private ownership of ground water attaches through ownership of the land surface, and the states have not enunciated or implemented jurisdiction in terms of allocation or administration of the resource.

State law and court decisions have generally dealt with surface and ground water as separable resources.

Most state statutes and court decisions do not recognize that pollution of both ground and surface water may result from the effects of activities not necessarily involving waste generation and disposal; pollution has been narrowly defined.

When these three weaknesses are considered in their total ramifications, it is evident that ground water pollution control is possible only within the context of a comprehensive management program for optimal allocation, conservation, protection, and use of the water together with related land resources available within a region.

The legal and institutional factors that must be considered in a ground water pollution control program are, as a consequence, largely dictated by the requirements of a management structure. Effective management of ground and surface waters as interrelated and interdependent resources is undertaken as a means of achieving regional, social, environmental, and economic goals. Implementation of such management requires that these goals be articulated; that management tools required to allocate the total water resource equitably among purposes, to abate and prevent pollution, and to equitably allocate the cost involved, be identified; and that government actions required for management be initiated and carried forward.

The objectives sought by managing ground and surface water resources on a conjunctive "systems" basis are not the same from area to area. Objectives that might be important in one area, such as extending the life of the ground water aquifer, protecting spring flows, or controlling subsidence, might have little relevance elsewhere. Many alternative institutional structures could be considered for the management vehicle. But the extremely diverse hydrologic, geologic, economic, legal, political, and social conditions affecting the occurrence, protection, and use of ground and surface waters in the United States suggest that no single structure would be universally applicable nor politically acceptable.

While management entities might not have the same organizational structure everywhere, certain geographic characteristics, fundamental resource information, and certain basic management powers and duties are commonly required. Delineation of the geographic area to be encompassed by a workable management entity must include consideration of areas having definable hydrologic boundaries. Furthermore, to the extent possible, the area should have social and economic identity or common interests and be generally contiguous with existing political subdivisions.

Data and analysis are needed regarding a range of hydrologic, geologic, physical, environmental, social, and economic factors that will largely determine the processes through which management objectives are attained. Through development of new analytical techniques by which the performance of a ground water basin under various conditions can be simulated or modelled mathematically, computerized management tools have become available. Depending upon their intended use, these models require adequate data (in appropriate formats and on a timely basis) such as the following:

Stream flow - normal and flood; water quality; waste discharges - quantity and quality; silt loads; precipitation; evaporation; storm and drought frequency, duration, and intensity; water supply facilities and costs; waste treatment processes and costs.

Water uses; water rights; projected uses; return flow -- quantity and quality; projected economic, demographic, and social trends; relationship between the factors affecting water quality such as source of pollutants, water development, water quality criteria and objectives.

Available energy sources, facilities, and costs; wildlife and fishery resources; recreational facilities and uses; historic, esthetic, and scenic areas; unique aquatic, zoologic, or biologic habitats.

Areas, sources, rate and quality of ground water recharge; surface and ground water inflow-outflow relationships; volume of aquifer storage capacity; aquifer transmissibility, specific capacity, and boundaries; volume of surface water storage; seasonal relationships of water demand and water in storage; relationships of surface and ground water use and quantity and quality of return flows.

Social Problems and Goals

Assuming that adequate programs are conducted to gather and make information available to a viable management entity, that entity must be vested with powers and authority to fully exercise a complex management function. Among these powers and duties must be the following as recommended by the National Water Commission (1972).

> "State laws should recognize and take account of the substantial interrelation of surface water and ground waters. Rights in both sources of supply should be integrated, and uses should be administered and managed conjunctively. There should not be separate codifications of surface water law and ground water law; the law of waters should be a single, integrated body of jurisprudence.
>
> Where surface and ground water supplies are interrelated and where it is hydrologically indicated, maximum use of the combined resource should be accomplished by laws and regulations authorizing or

requiring users to substitute one source of supply for the other.

The Commission recommends that states in which ground water is an important source of supply immediately commence conjunctive management of surface water (including imported water) and ground water, whether or not interrelated, through public management agencies.

The states should immediately adopt legislation authorizing the establishment of water management agencies with powers to manage surface water and ground water supplies conjunctively; to issue bonds and collect pump taxes and diversion charges; to buy and sell water and water rights and real property necessary for recharge programs; to store water in aquifers, create salt water barriers and reclaim or treat water; to extract water; to sue in its own name and as representative of its members for the protection of the aquifer from damage, and to be sued for damages caused by its operations, such as surface subsidence.

The states should adopt laws and regulations to protect ground water aquifers from injury and should authorize enforcement both by individual property owners who are damaged and by public officials and managment districts charged with responsibility of managing aquifers."

Implementation of the National Water Commission's recommendations would go far toward equipping a management entity to control ground water pollution. There are many other questions, however, largely unanswered in present statutes and court decisions, that will require very careful analysis.

References

1. Amer. Soc. of Civil Engineers, Ground Water Management, Manual on Engineering Practices No. 40, 216 pp (1972).

2. Banks, H. O., Federal-State Relation in the Field of Western Water Rights and Important Auxiliary Questions, Report prepared for the US Department of Agriculture, August (1967).

3. California Dept. of Water Resources, Planned Utilization of Ground Water Basins: Coastal Plain of Los Angeles County, Sacramento, 25 pp. (1968).

4. Corker, C. E., Ground Water Law, Management and Administration, National Water Commission, Report No. NWC-L-72-026 NTIS Accession No. PB 205 527, 509 pp (1971).

5. Davis, C., Riparian Water Law, A Functional Analysis, National Water Commission, Report NWC-L-71-020, NTIS Accession No. PB 205 004, 81 pp (1971).

6. Heath, M. S., Jr., A Comparative Study of State Water Pollution Control Laws and Programs, Water Resources Research Inst. Univ. of North Carolina, Rept. No. 42, 265 pp (1972).

7. Hines, N. W., Public Regulation of Water Quality in the United States, National Water Commission, Report NWC-L-72-036, NTIS Accession No. P 308 209, 632 pp (1972).

8. Mack, E., Ground Water Management, National Water Commission, Rept. NWC-EES-71-004, NTIS Accession No. PB 201 536, 179 pp (1971).

9. Meyers, C. J., Functional Analysis of Appropriation Law, National Water Commission, Rept. NWC-L-006, NTIS Accession No. PB 202 611, 72 pp (1971).

10. Moreland, J.A., and Singer, J.A., <u>Evaluation of Water-Quality Monitoring in the Orange County Water District, California</u>, USGS Open-File Rept., Menlo Park, Calif., 27 pp (1969)

11. Muckel, D.C., <u>Replenishment of Ground Water Supplies by Artificial Means</u>, Tech. Bull. No. 1195, Agric. Research Service, U.S. Dept. of Agriculture, 51 pp. (1959).

12. National Water Commission, <u>Review Draft of Proposed Report</u>, 2 vols., 1127 pp (1972).

13. Orlob, G.T., and Dendy, B.B., "Systems Approach to Water Quality Management," <u>Jour. Hydraulics Div.</u>, Amer. Soc. of Civil Engineers, vol. 99, no. HY 4, pp 573-587 (1973).

14. Santa Ana Watershed Planning Agency, California, <u>Final Report to Environmental Protection Agency</u> (1973).

15. Todd, D.K., <u>Ground Water Hydrology</u>, John Wiley & Sons, New York, pp. 200-218 (1159).

16. Trelease, F.J., <u>Federal-State Relations in Water Law</u>, National Water Commission, Rept. NWC-L-71-014, NTIS Accession No. PB 203 600, 357 pp. (1971).

*U.S. GOVERNMENT PRINTING OFFICE: 1974 582-412/31 1-3